Phenological characterization of wheat and barley through combined use of field and laboratory data

Kneubühler, Mathias ; Itten, Klaus I

Abstract: From the early days of remote sensing until today, there has been a wide range of applications of remote sensing data for agricultural management. Improvements in spatial, spectral and temporal resolution of available data products together with precision agriculture have resulted in an increase in the availability of services and products that help to manage agricultural operation more efficiently and profitably. Image-based remote sensing offers the potential to provide spatially and temporally distributed information for agricultural management. Remote sensing information can improve the capacity and accuracy of decision support systems (DSS) and agronomic models by providing accurate input information or as a means of within-season calibration or validation. Crop phenology is an important variable required by precision crop management systems (PCMS) in support of time-critical crop management (TCCM). Estimates of crop development, which are used for nutrient deficiencies detection, crop yield prediction or timing of forthcoming harvest are important in agricultural planning and policy making. In this paper, a methodology to track the main development stages of two cereals relevant for agricultural purposes and precision farming needs, based on hyperspectral data, is presented. An investigation of the suitability of four key parameters to track a crop stand's vitality and an error assessment are performed. Leaf area index (LAI), fraction of absorbed photosynthetically active radiation (FAPAR), water content and chlorophyll content are defined as the main parameters reflecting vitality and therefore alter with the plants' phenological stage.

PHENOLOGICAL CHARACTERIZATION OF WHEAT AND BARLEY THROUGH COMBINED USE OF FIELD AND LABORATORY DATA*

Mathias Kneubuehler and Klaus I. Itten

Remote Sensing Laboratories (RSL),
Department of Geography, University of Zurich, CH-8057 Zurich, Switzerland
Phone: +41 1 635 52 46, Fax: +41 1 635 68 46, E-mail: kneub@geo.unizh.ch

ABSTRACT

From the early days of remote sensing until today, there has been a wide range of applications of remote sensing data for agricultural management. Improvements in spatial, spectral and temporal resolution of available data products together with precision agriculture have resulted in an increase in the availability of services and products that help to manage agricultural operation more efficiently and profitably. Image-based remote sensing offers the potential to provide spatially and temporally distributed information for agricultural management. Remote sensing information can improve the capacity and accuracy of decision support systems (DSS) and agronomic models by providing accurate input information or as a means of within-season calibration or validation. Crop phenology is an important variable required by precision crop management systems (PCMS) in support of time-critical crop management (TCCM). Estimates of crop development, which are used for nutrient deficiencies detection, crop yield prediction or timing of forthcoming harvest are important in agricultural planning and policy making.

In this paper, a methodology to track the main development stages of two cereals relevant for agricultural purposes and precision farming needs, based on hyperspectral data, is presented. An investigation of the suitability of four key parameters to track a crop stand's vitality and an error assessment are performed. Leaf area index (LAI), fraction of absorbed photosynthetically active radiation (FAPAR), water content and chlorophyll content are defined as the main parameters reflecting vitality and therefore alter with the plants' phenological stage.

1.0 INTRODUCTION

Between April and August 1999 periodic observations of a spring wheat and a winter barley field have been performed in an intensively cultivated agricultural area, the Limpach Valley (470 m a.s.l.) located in Western Switzerland. Wheat is the most important cool-temperate cereal in the world, being followed by barley. Wheat cultivars cover more than 30% of Switzerland's acreage for agricultural products, barley is grown on over 15% of this area.

The selection of biophysical and -chemical variables to be investigated in this study is driven by their ability to track the phenological development of a plant. This implies detectable gradients of the observed data

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over time. In addition, it must be possible to ascertain them by means of reflectance measurements from a remote sensing device. Data collection included spectroradiometric measurements of the crop canopy, determination of leaf area index (LAI), fraction of absorbed photosynthetically active radiation (FAPAR), plant-, leaf- and grain-water content and chlorophyll content. The plant growth stage was characterized using a decimal code (DC) for the growth stages of cereals. According to the decimal code proposed by Zadoks et al. [20], the phenological development of crops can be divided into a vegetative, a generative and a reproductive phase. The vegetative phase consists of the growth stages *seedling growth* (DC 10-19) and *tillering* (DC 20-29), the generative phase of *stem elongation* (DC 30-39), *booting* (40-49), *inflorescence emergence* (DC 50-59), and *anthesis* (DC 60-69), the reproductive phase of milk development (DC 70-79), *dough development* (DC 80-89) and *ripening* (DC 90-99). Data takes were aimed at representatively cover all these phenological stages. Mean dates and durations of phenological stages of cereals can be found in literature [13].

2.0 METHODOLOGY

2.1. MEASUREMENT PLAN

Both, the spectral characterization of an agricultural stand's phenology and the retrieval of quantitative information of plant variables from spectral data describing the stand's vitality status depend on accurate measurements. A standardized measurement plan, incorporating spectral data takes and acquisition of plant vitality parameters was developed. Sampling strategy considerations are based on temporal and spatial requirements as well as sample size considerations. Field and laboratory measurements consist of:

- *Spectroradiometric measurements of the vegetation canopy using an ASD-Field Spectrometer covering the wavelength range from 400 nm to 2500 nm* [1]. To satisfactorily characterize the spectral variability within the crop fields, 50 to 60 reflectance measurements were recorded, performing stratified random sampling accross a transect along the diagonal of one half part of the fields under investigation. Each measurement taken was visually described as being of dense, medium or low vegetation cover.
- *Determination of leaf area index using a LICOR LAI-2000 Meter* [19]. Acquisition of about 20 LAI measurements was performed in the same manner as for the spectroradiometric measurements. Since LAI data strongly depends on the canopy architecture and the illumination geometry which vary both during the day, the measurements were carried out around solar noon, weather permitting.
- *Determination of the fraction of absorbed photosynthetically active radiation (FAPAR) by the canopy using a ceptometer* [8]. FAPAR measurements were carried out based on the following equation [11]:

  $$FAPAR = 1 - \frac{PAR_r + (PAR_t - PAR_s)}{PAR_o} \quad ,$$

  where PAR_r upward radiation at the top of the canopy, PAR_t downward radiation at the bottom of the canopy, PAR_s radiation reflected at soil surface, and PAR_o incoming radiation at the top of the canopy.

  To measure FAPAR in the field, the abovementioned radiation fluxes must be measured independently. Approximately 20 FAPAR values were recorded for each of the two agricultural stands per measurement day. The data was acquired randomly along a transect, and characterized as being of dense, medium or sparse vegetation coverage.
- *Determination of plant-, leaf- and grain-water content*. Plant-, leaf- and grain-samples of a mean

vegetation stand were collected and placed in a drying oven at 85° C for 48 hours (weight constancy). The weight and leaf area of the fresh samples were measured before drying to determine the water content from weight loss.

- *Determination of leaf chlorophyll content*. Leaf samples were collected in the field and taken to the laboratory for chlorophyll extraction. The photometric determination of chlorophyll a and b was performed with a CADAS-100 Spectrophotometer [14] in 100% acetone using the equations of Lichtenthaler [15]. The leaf area of each leaf was determined using a LICOR LI-3100 Leaf Area Meter [16].
- *Characterization of the growth stage of each measurement day using a decimal code for growth stages of cereals* [20].

2.2. DATA ANALYSIS

Each of the four parameters chosen to track the vitality status of a crop stand (LAI, FAPAR, water content, chlorophyll content) is related to the spectral data (Figure 1) of the corresponding phenological stages, The applied methods are described below.

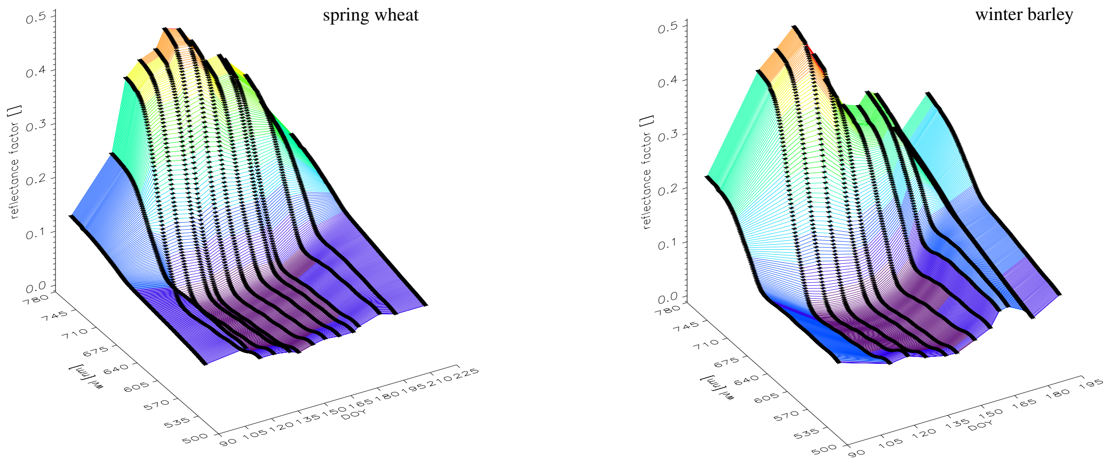

Figure 1: Mean spectral data of the 550-780 nm wavelength range of the observed spring wheat (left) and winter barley (right) field over a vegetation period. Especially the *senescing phase* of winter barley is heavily influenced by weeds.

2.2.1 Estimating LAI

LAI estimation is based on a semi-empirical reflectance model that calculates LAI of a green canopy based on the WDVI (weighted difference vegetation index) and the inverse of an exponential function [5][6]. The WDVI is a weighted difference between the measured reflectances $\rho(\lambda_{NIR})$ and $\rho(\lambda_{RED})$ assuming that the ratio of these two reflectances is constant for a certain type of bare soil. In this way, the influence of soil background is corrected:

$$WDVI = \rho(\lambda_{NIR}) - C \cdot \rho(\lambda_{RED}) \quad ,$$

where $C = \dfrac{\rho_{SOIL}(\lambda_{NIR})}{\rho_{SOIL}(\lambda_{RED})}$

The LAI is then calculated as: $$LAI = \frac{-1}{\alpha} \cdot \ln\left(1 - \frac{WDVI}{\rho_{\infty}(\lambda_{NIR})}\right) \quad ,$$

where α describes the rate at which the abovementioned function runs to its asymptotic value, and $\rho_\infty(\lambda_{NIR})$ is the asymptotic limiting value for the WDVI. Parameters α and $\rho_\infty(\lambda_{NIR})$ must be estimated empirically from a training set.

2.2.2 Estimating FAPAR

The fraction of photosynthetically active radiation is often expressed as an exponential function of LAI [2]:

$$FAPAR = A \cdot [1 - B \cdot \exp(-C \cdot LAI)] \quad ,$$

where *A, B, C* must be estimated empirically from a training set.

2.2.3 Estimating Water Content

Although the spectral reflectance properties of vegetation canopies are determined primarily by the absorption and scattering processes within the plant material and the stand's structure, superimposed effects of absorption by water and biochemical constituents can be found. Early studies by Gates et al. [10] and Sinclair et al. [18] showed that in the near- and shortwave-infrared region, a negative relationship between leaf water content and leaf reflectance can be found. Water content determination of a whole plant canopy is highly influenced by canopy characteristics, making reflectance a mixture of contributions from plant biochemicals, canopy structure and soil background contribution. Since water content and green biomass are positively correlated, observed high positive correlations between canopy water content and reflectance values in this region [17] are basically caused by biomass and not by water itself. Nevertheless, this relation bears the potential for canopy water estimation from remote sensing data in the near-infrared region. In this study, determination of plant water content is performed using stepwise multiple linear regression from wavelengths showing highest correlation of measured water content and corresponding spectral data for all phenological stages available. Plant water content c can be expressed as:

$$c = a_0 + \sum_{i=1}^{n} a_i \cdot \rho(\lambda_i) \quad ,$$

where c is the plant water content, n the number of wavelengths λ_i used in the regression model, a_0 the regression constant, $a_{i=1,n}$ the coefficients of the selected regressor wavelengths λ_i, and $\rho(\lambda_i)$ the reflectances of the selected regressor wavelengths λ_i between 400-1800 nm.

2.2.4 Estimating Chlorophyll Content

Most non-destructive techniques for the determination of chlorophyll relate the leaf reflectance at about 675 nm to the concentration of the total chlorophyll. Chappelle [4] used ratio spectra that allow the identification of reflectance bands corresponding to the absorption bands of specific pigments. The developed *ratio analysis of reflectance spectra* (RARS) *algorithm* allows estimation of the conentrations of chlorophyll a and b per unit mass solvent using a linear relationship. Blackburn [3] describes the relationship of $RARS_a$ with canopy chlorophyll a concentration per unit area using an exponential function. $RARS_b$ is reported to have no relationship with chlorophyll b.The algorithms for chlorophyll a and b are defined as follows:

$$RARS_a = \frac{\rho_{675}}{\rho_{700}} \quad \text{and} \quad RARS_b = \frac{\rho_{675}}{\rho_{650}} \cdot \rho_{700} \quad ,$$

where ρ_i is the reflectance at the wavelength *i*.

Blackburn developed the *pigment specific simple ratio* (PSSR) *algorithm.* An exponential function is reported to best describe the relationship of PSSR and chlorophyll a and b concentration. $PSSR_a$ and

$PSSR_b$ are defined as follows [3]:

$$PSSR_a = \frac{\rho_{800}}{\rho_{680}} \quad \text{and} \quad PSSR_b = \frac{\rho_{800}}{\rho_{635}}$$

In this study, both, RARS and PSSR were applied to the spectral data and laboratory chlorophyll data.

3.0 RESULTS

3.1. LAI

Although the concept of estimating LAI from WDVI was developed for green vegetation [5][6], it is reported to be likewise applicable to the phenological stages of flowering and ripening [7], when LAI and photosynthetic activity decrease. In this study, the growth stages of the vegetative phase and the generative phase until the beginning of anthesis (flowering) are subsequently referred to as *growing phase*, the stages of anthesis and the following reproductive phase are referred to as *senescing phase*.
Best results for LAI estimation from WDVI were found for separate treatment of the *growing* and the *senescing phase*. The combined use of the two datasets of spring wheat and winter barley for LAI estimation yielded the best results:

- The *growing phase* (solid lines in Figure 2) of both wheat and barley is best described by a joint dataset of both cultivars over the whole cropping cycle. Fit-parameters for LAI estimation from WDVI of both spring wheat and winter barley can be used interchangeably.
- The *senescing phase* (dashed lines in Figure 2) of both wheat and barley is best described by a joint dataset of both cultivars over the *senescing phase*. Especially LAI estimates in the *senescing phase* are more accurate under absence of data from the g*rowing phase*.

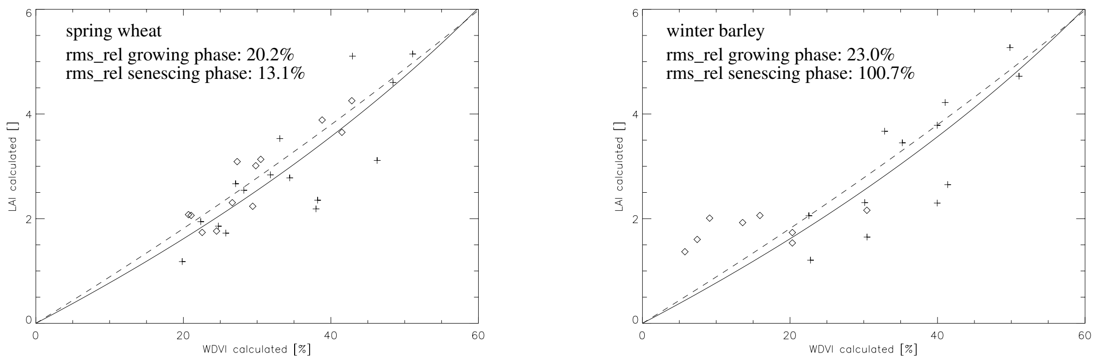

Figure 2: Fitted relationship between WDVI and LAI for spring wheat (left) and winter barley (right). The solid line represents the exponential fit for the *growing phase*, the dashed line for the *senescing phase*. Crosses denote WDVI values and corresponding measured LAI of the *growing phase*, rhombs WDVI values and measured LAI of the *senescing phase*. The presence of weeds and standing litter material strongly deteriorates LAI estimation of winter barley from WDVI towards the end of the cropping cycle.

LAI estimates of winter barley in the *senescing phase* suffer from heavy weed infestation during ripening. This disturbs both LAI-2000 meter readings and spectroradiometric measurements (WDVI values). In addition, the LAI-2000 meter's measurement design, which is based on a radiation interception method involving all elements of a vegetation canopy's architecture, such as green leaves, litter and ears, tends to overestimate LAI of a crop stand mainly towards the end of a vegetation period [19]. As a consequence, it can be concluded, that LAI estimates based on the joint dataset of *senescing* spring wheat and winter barley yields more accurate results of LAI of winter barley towards the end of the cropping cycle than can actually be indicated by the applied accuracy investigation of Figure 2.

3.2. FAPAR

A plant's capacity to absorb incoming radiation for biomass production is dependent on its physiological state and therefore related to its phenological stage. Highest LAI values for spring wheat were measured during stem elongation for DC 32-33 (2^{nd} to 3^{rd} node detectable). Highest FAPAR values were recorded on the same day. LAI and FAPAR values stay constantly high until completion of anthesis.
Winter barley showed highest measured LAI and FAPAR values during inflorescence emergence (DC 55-59). Contrary to spring wheat, the ears of winter barley are larger and tend to bend sideward, preventing incoming radiation from penetrating the canopy, which leads to highest observed LAI and FAPAR readings. Estimation of FAPAR can be performed using an exponential relationship with LAI. The fitted relationship between modelled LAI values derived from WDVI (see chapter 3.1) and measured FAPAR for spring wheat, winter barley and a joint dataset are presented in Figure 3 (left). Based on the derived fit parameters, FAPAR can be modelled over the cropping cycle (Figure 3, right).

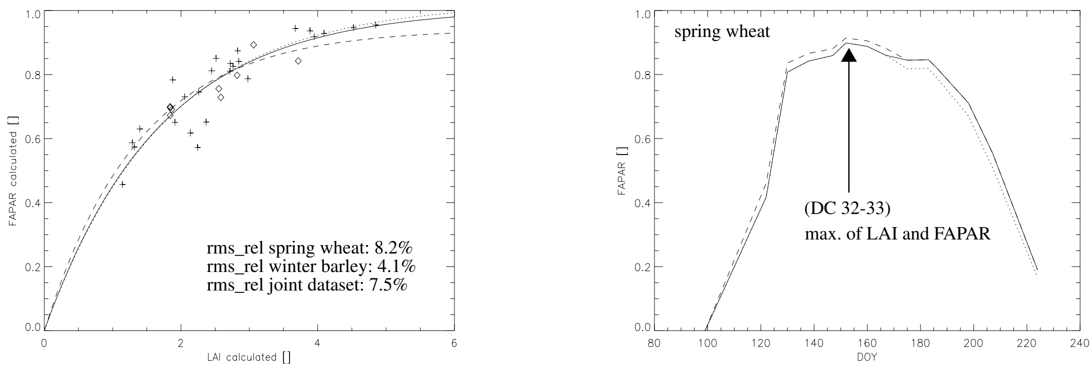

Figure 3: Left: Fitted relationship between LAI values derived from WDVI and measured FAPAR values for spring wheat (dotted line), winter barley (dashed line) and a joint dataset (solid line). Crosses denote LAI values and corresponding, measured FAPAR values of spring wheat, rhombs LAI values and corresponding, measured FAPAR values of winter barley. Right: Modelled FAPAR of spring wheat over the cropping cycle (solid line: FAPAR from optimal fit parameters for separate treatment of *growing* and *senescing phase*; dashed line: FAPAR from LAI based on fit parameters of *senescing phase*; dotted line: FAPAR from LAI based on fit parameters of g*rowing phase.*

3.3. WATER CONTENT

Water content determination in the laboratory was performed for plant-, leaf- and grain-samples. As a general trend, water content decreases from the early stages of plant growth towards the end of the cropping cycle. Whereas plant- and grain-water content decrease steadily towards the end of the *senescing phase*, leaf-water content decreases abruptly from the water ripe stage (DC 71), clearly marking the beginning of the reproductive phase.
Since spectroradiometric measurements of a crop canopy, as recorded by a remote sensor, do not represent single leaves, but a whole plant, the extraction of plant-water content from spectroradiometric data was investigated. Determination of predictive wavelengths λ_i, the regression constant a_0 and regression coeffi-

cients a_i was carried out on a calibration dataset of measured plant-water content and corresponding spectral data for all phenological stages available. First derivative analysis of the wavelength dependent correlation coefficient *r* was applied to select predictive spectral wavebands, that are consecutively entered into a stepwise multiple linear regression. The optimal number of regressor wavelengths λ_i was determined by a maximum multiple coefficient of determination R^2 and a minimum *relative rms* of a verification data set (Figure 4).
The phenological stages of the reproductive phase (milk development (DC 70-79), dough development (DC 80-89) and ripening (DC 90-99)) show characteristic water contents of the grains [20]. Strong linear correlations (r=0.99) of plant-water content and grain-water content were found for the time between DC 71 (caryopsis water ripe) and DC 92 (caryopsis hard) under dry atmospheric conditions. Nevertheless, humid conditions around the stage of hard dough (DC 87) can prevent the grains from loosing moisture and reaching the desired grain moisture content of 15% at harvest (DC 92). This effect disturbs the linear relationship between plant- and grain-water content.

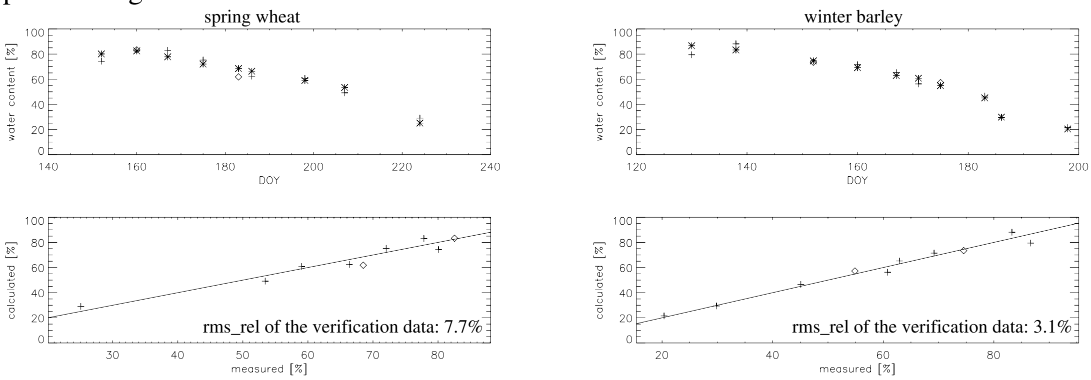

Figure 4: Determination of plant water content of spring wheat (left) and winter barley (right) using stepwise multiple linear regression. Asterisks denote plant water content as measured in the laboratory, crosses are water content values from the calibration set of the multiple regression and rhombs are water content values calculated for validation of the regression equation.

3.4. CHLOROPHYLL CONTENT

Several studies have demonstrated that determination of leaf chlorophyll content from spectroradiometric data is possible [12][4][11][3], whereas chlorophyll determination of spectral data from vegetation canopies suffers from influences of the total biomass (LAI) [9]. The algorithms applied in this study were originally developed for soybean leaves (RARS) and senescent tree leaves (PSSR) and applied to a canopy of bracken throughout a growing season [3]. None of the methods were applied to agricultural crop stand canopies.
The application of RARS and PSSR to the data of the observed spring wheat and winter barley fields shows strong variations with chlorophyll a and b content per unit area. Nevertheless, the strong relationship between the reflectance ratioes and chlorophyll concentrations using an exponential function, as described in literature, can not be found for the two data sets under investigation. It must be concluded that the two algorithms are not able to track chlorophyll of plants that undergo such fundamental physiological changes over a cropping cycle as crop stands do, by an exponential function.
In addition, calculations of the absolute feature height and feature width of the 675 nm chlorophyll a absorption feature show high correlations with LAI derived from WDVI. Only weak correlations with chorophyll concentrations can be found. Therefore, the spectral response of a vegetation canopy around the main chlorophyll a absorption region (675 nm), as seen by a remote sensing device, is predominantly driven by green biomass (green LAI), not chlorophyll per leaf area. This makes chlorophyll estimation of a crop stand over a vegetation period impossible, using the abovementioned spectral region.

4.0 CONCLUSIONS

As far as the suitability of the four observed parameters (LAI, FAPAR, water content and chlorophyll content) is concerned in tracking the phenological stages of winter barley and spring wheat, it can be concluded, that the estimation of LAI, FAPAR and plant water content from hyperspectral measurements is possible within the specified accuracies, whereas chlorophyll estimation was not successful due to canopy structural effects (LAI) present in the observed spectral region. The comprehensive collection of ground truth data during the 1999 field campaign bears the potential to relate retrieved LAI, FAPAR and water content values of spring wheat and winter barley from future hyperspectral data takes to specific phenological stages.

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